Method and system for extracting spine frontal geometrical data including vertebra pedicle
locations

Field of the Invention

The invention relates to an image processing method for extracting frontal
geometrical data of a spine image including vertebra pedicle locations. The invention finds its
application in medical imaging.

5   Background of the Invention

A segmentation method applied to the spine is already known of the
publication "Digital Radiography Segmentation of Scoliotic Vertebral Body using
Deformable Models" by Claude Kauffmann and Jacques A. de Guise in SPIE Vol.3034,
pp.243-251.This publication describes a computer segmentation method based on the active
10   contour model (g-snake) and using a prior knowledge. This method is adapted and used to
detect automatically the contour lines of each vertebral body independently in digital
radiographs of the scoliotic spine. These contour lines are used to identify correspondent
anatomical landmarks for the 3D reconstruction of the scoliotic spine using a bi-planar
technique. The steps comprise: constructing a standard template for each kind of vertebrae
15   (thoracic or lumbar), performing three best fits of the appropriate template on the spine
radiograph, g-snake energy minimization, selection of a best contour for each vertebra
individually, and anatomical landmark extraction (including corners and spine center-line
points). Previous steps of digitization of the spine centerline and acquisition of a prior
knowledge including the height and width of the standard template are first performed.

20   Summary of the Invention

The method known of the cited document does not describe steps for
specifically extracting the landmark corresponding to the location of the spine pedicles. It
only provides the corner locations. Now, the pedicle locations are particularly useful to
estimate the rotation angle of every vertebrae.

25   The present invention has for object to propose a image processing method to
extract spine data called landmarks corresponding to the pedicle locations. This method has
steps to perform the extraction of these pedicle landmarks using previously determined
locations of other landmarks corresponding to the vertebra corner projections. For example,
these steps are carried out by processing a frontal image of a number of adjacent vertebrae of

the spine. Such an image processing method is claimed in Claim 1. An imaging system, an X-ray apparatus and a computer program product are also claimed to carry out the method.

These extracted geometrical data permit of providing information appropriate to help diagnosing scoliosis even on a single 2-D image. Said data also permit of three-dimensional image reconstruction of the spine from two bi-planar images using a technique of geometric modeling. Three-dimensional images of the spine particularly help diagnosing scoliosis because said disease is a 3-D deformity of the spine. The construction of the 3-D model of the spine is based on the location of the corner landmarks and the pedicle landmarks of the spine vertebrae.

Brief Description of the Drawings

The invention is described hereafter in detail in reference to diagrammatic figures, wherein:

FIG.1A, FIG.1B, FIG.1C are representations of a vertebra in various perspectives;

FIG.2A and FIG.2B show optimal landmarks of a vertebra, in frontal and lateral views;

FIG.3A and FIG.3B illustrate the step of positioning of the vertebra in a local referential;

FIG.4A shows a spine frontal view and FIG.4B shows icons of successive vertebrae, each icon representing the features of the vertebra in its local referential;

FIG.5A represents a particular vertebra and FIG.5B represents the corresponding icon;

FIG.6A shows, superimposed on an icon, a curve of feature accumulation and FIG.6B shows the corresponding curve of Costs ;

FIG.7A is the curve of Costs for the determination of a couple of pedicles and FIG.7B is a 3-D Cost Matrix for determining the best paths where the left and right pedicles are to be found along the spine;

FIG.8 is a functional block diagram of medical diagnostic imaging system and apparatus for carrying out the method.

Description of embodiments

The invention relates to an image processing method for extracting geometrical data of the spine, in order to localize specific elements of the spine in spine images, for studying spine deformities. The specific elements are the pedicles of the vertebrae.

Referring to FIG.1A to FIG.1C, in perspective views, a vertebra shows a body 7, which defines the spine axis and the shape of the vertebral discs and which is substantially cylindrical with flattened elliptic bases 1, 2 called endplates (FIG1A, FIG.1C); a spineous process 4 located in the plane of symmetry of the vertebra (FIG.1A, FIG.1B); two transverse
5   processes 3 (FIG.1A, FIG.1C) and two pedicles 5 located at the bases of the vertebral arches (FIG.1A, FIG.1B); the pedicles define the intrinsic rotation of the vertebra around its axis.

Six optimal landmarks are selected, as represented respectively in the frontal and in the lateral images shown in Fig.2A and FIG.2B. These landmarks are the extremities of the projection of the vertebra body, which are the corners A, B, C, D, A', B', C', D' of the
10   vertebra; and the position of the inner points E, F of the projection of the pedicles, further on called pedicle landmarks. The present method supposes that the corners A, B, C, D of the interesting vertebrae have already been located in a frontal view. This method comprises steps of:

A frontal image of an examined patient is acquired. This image may be formed
15   by X-ray imaging, as shown in FIG.4A. Each point has a luminance intensity and coordinates in a cartesian referential whose axes are parallel to the sides of said frontal view. The frontal view may comprise a number of adjacent vertebrae, for example sixteen (16) vertebrae. The processing method encounters problems due to the position of the pedicles with respect to the other landmarks in the different vertebrae along the spine. In the thoracic vertebrae, the
20   pedicles are almost at the same height as the upper endplate or even higher and they are very difficult to detect. In the lumbar vertebrae the pedicles are in the upper half of the vertebrae and they are easier to detect. The vertebrae have individual axes of rotation that are generally not vertical and that are different from each other.

Each vertebra is processed separately in order to take advantage of the local
25   intensity properties for pedicle detection. In the region of the processed vertebra, the sides of the vertebra present a high contrast, which would interfere in the detection of the pedicles. In order to prevent this interfering, a restricted Region of Scanning is defined, which is a part of the image to be processed for pedicle detection. To this end, each vertebra is attributed an independent cartesian referential in which the Region of Scanning is further defined.

30   Referring to FIG.3A, the current frontal original vertebra image shows the corner landmarks A, B, C, D. The middle points of the left and right lines joining the corners, respectively CA, DB, are denoted O_1 for AC and O_2 for BD. The coordinates of these middle points O_1, O_2 are computed in the referential of the frontal view. The line O_1O_2 that goes through these points is an axis X' that is generally not horizontal as above-described. The

orthogonal axis Y' going through the center O of O_1O_2, is generally not vertical. A new
referential X, Y is determined with a horizontal axis X and a vertical axis Y. The Region of
Scanning is obtained by rotating a part of the of the current frontal original vertebra image
using a rotation angle θ that is the angle between the X'–axis and the current horizontal axis
5   defined in the frontal view. The new X-axis is parallel to this current axis. The center of the
rotation is O and the part of the image to rotate is determined by the largest projections of the
corners A, B, C and D onto the new X-axis.

        Referring to FIG.3B, the part of the image resulting from said rotation is
rectangular with O as the center and constitutes the Region of Scanning. It is delimited by
10   horizontal lines parallel to the X-axis at the ordinates Y_0, Y_E, and by vertical lines parallel to
the Y-axis at the abscissae X_0, X_E. So, the Region of Scanning in this new referential X, Y is
defined by the rightmost projection of corners A and C onto the X-axis leading to X_0, the
leftmost projection of corners B and D onto the same X-axis leading to X_E. The same
procedure for the Y-axis leads to Y_0 and Y_E. The Region of Scanning is defined by New
15   Corners that are $A_0(X_0, Y_E)$, $B_0(X_E, Y_E)$, $D_0(X_E, Y_E)$, and $C_0(X_0, Y_0)$.

        Features that are characteristic of the points found in said Region of Scanning
are estimated. The results of this operation of Feature Estimation permits of constructing an
Image of Features in the local referential X, Y of the Region of Scanning. Different features
can be considered for pedicle detection, such as gradient values, gray levels or intensity
20   variance. The features that are considered as most effective to discriminate the thin structures
representing the pedicles are ridgeness values.

        The image of the Region of Scanning can be a positive image, which is
considered as a 3-D picture, having two dimensions for the co-ordinates of pixels and a third
dimension for the intensity signals associated to said pixels. A ridge is a crest-like structure
25   formed by adjacent pixels having intensity signals that are maximum in a neighborhood, said
pixels having specific dispositions the ones with respect to the others resulting in specific
gradient values with respect to orientations. A ridge pixel shows a low intensity gradient in a
first determined direction in its neighborhood, and shows an intensity gradient that is
maximum in a direction perpendicular to said first direction. The more a given structure is
30   formed of pixels verifying this gradient property, the more the ridgeness measure of the
structure is high. Instead of ridges, troughs can be considered in a negative original image of
the Region of Scanning for instance obtained by X-ray imaging. In an X-ray negative image,
a ridge structure is a dark structure on a lighter background. In this case, the calculations for
extracting the pedicles have for an object to extract trough pixels, which can be determined

by measures similar to ridgeness calculations. In ridgeness calculations applied to troughs determination, the estimation of specific intensity gradients that is required for characterizing ridges is still valuable for characterizing troughs. So, in the description of the present method, these calculations are called "ridgeness" calculations, whether they are applied to ridges or

5   troughs in the Region of Scanning.

FIG.5A shows an original frontal image of a vertebra. The method comprises a step of "ridgeness" calculation applied to the image of the Region of Scanning corresponding to the vertebra of FIG.5A. This "ridgeness" calculation is performed by applying, on the pixels, filters known as ridge-filters, which determine the pixels of the ridge or trough

10   structures. Based on this ridgeness calculation, each pixel of the Region of Scanning is further associated to a ridgeness data. The resulting image is called Feature Image as shown on FIG.5B.

Preferably, in a variant of this step of Feature Image formation, the features are computed on a Region of Interest ROI, which is constituted of a number of adjacent

15   vertebrae and of a border region around these vertebrae represented in a frontal view such as the view shown on FIG.4A. From this Feature computation in the ROI, an image called ROI Feature Image is formed. The calculation of various new referentials by rotation and the calculation of various limited Regions of Scanning in said new referentials, as above-described, are then further performed based on said ROI Feature Image. FIG.4B shows

20   various icons of Feature Images corresponding to said various Regions of Scanning. The icon 2 of FIG.4B is a Feature Image corresponding the circled vertebra of FIG.4A. The icon 1 is a Feature Image of a vertebra above the circled one and the icons 3 to 10 are Feature Images of the successive vertebrae below this circled one.

For every vertebra, the contrast of the Feature Image, in each icon

25   corresponding to the Region of Scanning, is preferably further linearly enhanced. This Feature Image is scanned parallel to the vertical Y-axis, and the Feature values are accumulated by summing, in the direction of the Y-axis for every X coordinates between X_0 and X_E, called X-Region. Actually, this accumulation may be limited to be computed only on the upper-region of the vertebral body. This upper-region may be defined as covering only

30   70% of the length of the Y-axes of the Region of Scanning, since the pedicles are usually located on this upper-region. Avoiding to scan the lowest part of the Region of Scanning enables to avoid taking into account the lower endplates, thus avoiding interfering disturbances, and enables to reduce calculation amount.

Referring to FIG.6A, the summed Feature Values are projected onto the horizontal X-axis. This operation results in a curve of the Accumulated Feature Values, called AS, showing maximum values called Peaks corresponding to the occurrence of ridges substantially parallel to the vertical Y-axis. The curve S is superimposed onto the Feature Image inverted in intensity.

These Accumulated Values are further transformed into Local Costs. In this step of Local Cost calculation, an inversion operation is required for providing a correspondence between the highest Accumulated Values or Peaks of the curve AS and lowest Local Costs. The X-region is split into two parts: a left part and a right part. For both parts independently, the Accumulated Values are submitted to a threshold operation. As an example, a threshold is set at 80% of the average level of the Accumulated Values. So, LC being the associated Local Cost:

LC = 0 when associated to the highest Accumulated values;

LC = 1000 when associated to an Accumulated Value equal to the predetermined threshold level;

LC is infinite when associated to every location on the X-axis where an Accumulated Value is found to be below the predetermined threshold level.

For the other locations, an associated cost LC is computed as the inverse of the corresponding Accumulated Value: a precise equation being for example:

$$LC = 1000 * \left(1 - \frac{AS - \overline{f\,AS}}{M_S} \right)$$

where f the threshold level, S is the Accumulated Value, $\overline{AS}$ is its average and M_S its maximum value. FIG.6A shows the accumulation curve and FIG.6B shows the local cost curves for the vertebra presented in FIG. 5A, 5B. In Fig.6B, for visualization purpose, the image of the vertebra features are included, with reversed contrast, on the background of the graphs, as in FIG.6A. It is to be noted that the cost graph has been limited to a 0-2000 range but actually goes to an INFINITE COST, which is defined at 10^9, with 1000 limiting the useful region.

Projected pedicles mostly look like thin vertical lines. The pedicle landmarks of FIG.2A situated on said thin lines are detected in the frontal view. As shown on FIG.2A, pedicle projections are elliptical-shaped. The left and right external borders of the elliptical-shaped pedicles may be a source of errors. According to the present method, the Y-accumulation procedure is used to perform a discrimination between the left and the right

borders of each elliptical shaped pedicle. The Feature Images may include some other sources of errors that are the borders of the vertebra, which also show high feature response and which are vertical, and the projection of the spurious process, which may appear as a vertical line roughly in the middle of the vertebral body but mostly in the lowest part of the body. According to the present method, the effects of these possible errors will be reduced by a further Dynamic Programming procedure.

It is important to note that only the internal border locations of the pedicles are looked for, because only these locations are used to estimate the rotation of the vertebra for diagnosing the severity of spine scoliosis. The pedicle landmarks that are on the internal border locations of the left and right pedicles are respectively called Left and Right Pedicle Locations. As explained previously, the present method has for an object to simultaneously detect the Left and Right Pedicle Locations for the specific spine vertebra of a specific patient. For performing this operation, the couples of Left and Right Pedicle Locations, which are represented by couples of corresponding abscissae X_L, X_R on the X-axis, are looked for, for all vertebrae. Since a Local Cost is associated to each abscissa on the X-axis, couples X_L, X_R showing the lowest Costs are looked for, for each vertebra. For each given Left Pedicle Location X_L, several Right Pedicle Locations X_R are possible, thus forming several couple candidates of Left and Right Pedicle Locations. For estimating the best couple candidates:

the whole Region of Interest ROI of the spine is considered in order to take into account the locations of each couple candidate of a given vertebra with respect to the other couple candidate of the other vertebrae, which give more robustness in the location determinations;

the location of each vertebra in the spine, called state, is defined by a vertebra index V, which is the name or the position of said vertebra in the spine, and a Database is accessible to provide average values of the distance, hereafter called Pedicle Distance, separating candidate couples of Left and Right Pedicle Locations, for each given vertebra;

every possible Left Pedicle Location is determined in a range of coordinates between X_0 and the middle of the X-Region (middle of $X_0 X_E$), and

a certain number of position candidates for the Right Pedicle Location is determined, typically in ten (10) bands called "bins", gathering 1 to 3 Right Pedicle Location candidates;

The procedure of finding Right Pedicle Locations P_R, called P_R candidate, from a given particular Left Pedicle Location P_L, called P_L candidate, comprises:

searching for P_R candidates at a distance $\overline{D_{L,R}}$ estimated from the database, within a range proportional to the standard deviation to this distance, thus defining a search region;

dividing this search region into a number of bins, favorably ten (10) bins, of equal size;

5   selecting the same number (10) of P_R candidates, one for each bin. If one bin is found empty, an infinite cost is applied. If several P_R candidates are inside the same bin, the P_R candidate having the minimum local cost is selected. Thus for every P_L candidate, a set of said number of for example ten (10) P_R candidates is built.

computing the local cost associated with one state, defined by the vertebra index V,
10   with the P_L candidate and with an associated P_R candidate, as the sum of three terms that are:

the Cost associated to the P_L candidate;

the minimum of the Costs associated to every P_R candidate in the current bin,

the deviation of the current distance $D_{L,R}$ between said P_L and P_R candidates with respect to the "average" distances $\overline{D_{L,R}}$ as estimated from the database. Actually the
15   distance term is normalized by the cosine of the rotational angle of the current vertebra estimated by using information from only the left location.

Referring to FIG.7A, the actual computation is performed according to:

$$SC(L, R) = LC_L + LC_R + \left(D_{L,R} - \overline{D_{L,R}} \right)$$

which is the State Cost SC(L, R) for associating possible P_L and P_R candidates, expressed as
20   the Sum of the Local Costs LC_L and LC_R at the indicated locations of said possible candidates, plus the difference between the actual distance $D_{L,R}$ between the locations of said candidates and the corresponding "average" normalized distance $\overline{D_{L,R}}$ for the given vertebra. It is to be noted that these Local Cost computations are performed for every vertebra and thus the previous equation depends upon V, the vertebra index. These State
25   Costs SC(V, L, R) are used for defining the Matrix-Costs of the 3D-state-Matrix illustrated on FIG7B.

A Dynamic Programming (DP) procedure is carried out in order to determine one Best Couple among the P_L and P_R candidates, for each vertebra of the spine, taking into account that for two successive vertebrae, the pedicles are substantially aligned (except in the
30   case of a vertebral displacement) and that for the whole spine, the paths on which the pedicles are disposed are substantially smooth. This Dynamic Programming (DP) is a non-iterative method, effective in contour detection, that uses Energy Functions and that is not

described hereafter, because it is well known of those skilled in the art. This procedure has for a purpose to determine the "most likely path" for the location of the P_L and P_R candidates. The points that are to be linked are those that are most likely part of the pedicle internal sides. The Dynamic Programming (DP) procedure calculates the Path of lowest Cost going from a

5   node to another to yield this Path. The DP is performed in the frontal view in the vertical direction.

          A 3-D Matrix of States is defined, as depicted in FIG.7B. This Matrix has a P_L-axis (vertical), for the number, for example 30, of P_L candidates; it has a P_R-axis (in the depth direction of FIG.7B) for the number of P_R bins (10 bins) per each P_L candidate; the P_L-

10   axis and the P_R-axis define a plane, regarded as a band (vertical band on FIG.7B) of the 3-D Matrix. The third dimension (horizontal) of this Matrix is the State given by the index V of the current vertebra under study among the number N of adjacent vertebrae that is user specified, typically 5 or 16 vertebrae.

          For carrying out the Dynamic Programming Procedure, a first pass, called

15   Forward Pass, is performed in a forward direction along the V-axis. In a first State (for a first vertebra), a first couple of P_L and P_R candidates, for instance denoted by P_{L1} , P_{R1}, is defined as the one with the lowest State Cost in the corresponding first band of the Matrix of States. The procedure has for an object to determine, in the following State (for the second vertebra), a couple of P_L and P_R candidates, for example denoted by P_{L2} , P_{R2}, which is one with the

20   optimum State Cost in this second State and which is linked to the first couple of the first State with the lowest Transition Cost. This Transition Cost is favorably the Sum of the distances between P_{L1}, P_{L2} and between P_{R1}, P_{R2}. This couple P_{L2}, P_{R2} that fulfils the Cost conditions in the second State is called Best Predecessor. So, for each State, the Best Predecessor is defined as the one with the lowest Path Cost. The search for this Best

25   Predecessor is actually performed by first looking for the P_L candidate that is the closest to the one of the current State (±10 locations). Then, for determining the best P_R candidate in said current State, a Path Cost is defined for linking the current State and its Predecessor State, composed of three Costs:

          the Local Costs of the previous State,

30   the State Cost of the current State,

          the Transition Cost that is the Sum of the Distances between the couples of P_L and P_R candidates and is intended to penalize sudden local variation of the rotational angle.

          A second pass, called Backward Pass, is performed in the backward direction. The Backward Pass determines, for every State, the most probable predecessor, i.e. the

Couple of the previous State that has the minimal Path Cost. The Backward Pass begins in
the State of the last vertebra having the lowest Path Cost. Going backwards, the Dynamic
Programming Procedure retrieves the locations for both pedicles for every vertebra. Thus, it
defines a line in the 3-D Cost Matrix. Two vertical lines are then drawn in the local
5   referentials to display the determined pedicle landmark locations for every linked vertebra.

The user can then select and move faulty lines towards correct locations. As
soon as he releases a line, the cost is modified such that a zero (0) Cost is associated to the
selected location and an infinite Cost is set for all the other locations in the current half
vertebra. The building of a new Cost Matrix is then performed, followed by a new Dynamic
10   Programming Procedure.

Referring to FIG.8, a medical examination apparatus 150 comprises means for
acquiring digital frontal image data of the spine, and a digital processing system 120 for
processing these data according to the processing method above-described. The medical
examination apparatus comprises means for providing image data to the processing system
15   120 which has at least one output 106 to provide image data to display and/or storage means
130, 140. The display and storage means may respectively be the screen 140 and the memory
of a workstation 110. Said storage means may be alternately external storage means. This
image processing system 120 may be a suitably programmed computer of the workstation
130, or a special purpose processor having circuit means such as LUTs, Memories, Filters,
20   Logic Operators, that are arranged to perform the functions of the method steps according to
the invention. The workstation 130 may also comprise a keyboard 131 and a mouse 132.